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Ocean Mass Density Calculations from Temperature and Salinity Data

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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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Aeronautical and Maritime Research Laboratory

ABSTRACT

Technical Report

A knowledge of the mass density stratification of ocean waters is a fundamental requirement when performing calculations in the field of dynamical oceanography. Experimentally, ocean temperature and salinity stratifications can be conveniently measured. In this report, details are given of a computational procedure which uses the International Equation of State of Sea Water (IES 80) to calculate an ocean mass density stratification from temperature and salinity data. The results of calculations are presented which yield mass density stratifications at a number of locations in waters to the West and North-West of Australia.

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EXECUTIVE SUMMARY

In this report, details are given of a computational procedure for calculating an ocean mass density stratification from temperature and salinity vs. depth data. The advantages of the procedure are its theoretical simplicity, and the fact that it may be used in an analogous manner to procedures commonly used to calculate sound speed profiles.

The report begins with a presentation of some general facts about ocean density, temperature and salinity stratifications. Specific details of the computational procedure are then presented. The procedure utilises the empirically determined International Equation of State of Sea Water (IES 80), and has been implemented in a FORTRAN computer program which appears in the Appendix. Finally, sea trials data obtained in waters to the West and North-West of Australia are analysed. The results show that the greatest density variations occur in more northerly waters where temperature variations are greatest. At depths below approximately 800 m the effect of pressure upon the density stratification dominates, yielding a linear density profile.

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Graham Furnell began his career within DSTO in 1973 as an apprentice Fitter and Turner. After the completion of his apprenticeship, he commenced studies towards a BSc at the University of Adelaide, and graduated with honours from the Department of Applied Mathematics in 1985. He was awarded a PhD from the same department in 1990 for a thesis entitled "A Study of Acoustic Wave Propagation within Curved Ducting Systems". While employed as a Research Scientist within DSTO, Dr Furnell has worked on tasks involving the study of radar scattering, submarine degaussing and the formation of submarine wakes. He is currently located within Maritime Operations Division, where he is working on sonar array processing problems.

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1. SOME GENERAL FACTS ABOUT DENSITY, TEMPERATURE AND SALINITY STRATIFICATIONS

The density of sea water ρ {kg m^{-3}}, varies as a function of its temperature t {C^0}, its salinity s {g kg^{-1}}, and, to a lesser degree (except at great depth), its pressure p {bar} (1bar $= 10^5$Pa). ρ increases if s increases, if p increases, or if t decreases. Measured values of ρ vary from about 1000 kg m^{-3} for almost fresh surface water, up to about 1070 kg m^{-3} at extreme ocean depths (10^4 m). The average density of sea water is close to 1027.6 kg m^{-3}. Density normally increases with depth simply because of the general tendency in Nature for a system to settle down in a state of minimum energy. The density does not increase uniformly with depth however, and the rate of increase is influenced by local values of the water's temperature and salinity. For convenience, the density of sea water is often expressed via the quantity *sigma-t*, which is defined by the relation

$$\sigma_t = \rho - 1000. \tag{1}$$

Hence, the density $\rho = 1027.6$ kg m^{-3} is equivalently specified by $\sigma_t = 27.6$. Note that it is common practice not to quote the units of σ_t when writing its numerical value.

A good presentation of some general facts concerning the distribution of ocean temperature and salinity is given in reference [1]. The following are quotes from that reference:

"The open ocean surface temperature decreases from values as high as 28^0 C just north of the equator to nearly -2^0 C near ice at high latitudes both north and south". "Below the surface the water can usually be divided into three zones in terms of its temperature structure. There is an upper zone of 50 to 200 m depth with temperatures similar to those at the surface, a zone below this extending from 500 to 1000 m in which the temperature decreases rapidly, and a deep zone in which the temperature decreases more slowly. Typical temperatures at low latitudes would be 20^0 C at the surface, 8^0 C at 500 m, 5^0 C at 1000 m and 2^0 C at 4000 m".

"The depth at which the temperature gradient (rate of decrease of temperature with increasing depth) is a maximum is called the *thermocline*. With actual observations of temperature in the sea it is sometimes difficult to determine this depth accurately because of minor irregularities in the temperature/depth profile and it is easier to pick out a *thermocline zone* as a range of depths over which the temperature gradient is large compared to that above and below. Even for this *zone*, it is often hard to define precisely the depth limits, particularly the lower limit, and one must accept some degree of approximation in stating the depth limits of the thermocline zone. However, in low and middle latitudes it is clear that there is a thermocline present all the time at depths between 200 and 1000 m. This is referred to as the *main* or *permanent* thermocline. In polar waters there is no permanent thermocline".

"The range of surface salinity values in the open ocean is from 33 to 37 g kg^{-1}. Lower values occur locally near coasts where large rivers empty and in polar regions where ice melts. Higher values occur in regions of high evaporation such as the eastern Mediterranean (39 g kg^{-1}) and the Red Sea (41 g kg^{-1}). On the average the North Atlantic is the most saline ocean at the surface (35.5 g kg^{-1}), the South Atlantic and South Pacific less so (about 35.2 g kg^{-1}) and the North Pacific the least saline (34.2 g kg^{-1})."

"The salinity distribution in the vertical direction cannot be summarized quite as simply as the temperature distribution. In the upper water the reason for this is that density, which is the factor determining the stable position of a water body in the vertical direction, is determined chiefly by temperature in the open ocean (except the polar seas). Therefore, water of higher temperature (lower density) is generally found in the upper layers and water of lower temperature (higher density) in deeper layers. The variations in salinity which occur in open ocean waters are usually not sufficient in their effect upon density to override the effect of temperature. Therefore it is quite possible to have either high or low salinity in the warmer surface and upper layers".

"In deep waters, 4000 m and deeper, the salinity is relatively uniform at 34.6 to 34.9 g kg^{-1} through the world ocean. Remembering that the deep water temperature also has only a small range (-0.9^0 to 2^0 C) this means that the deep water environment is very uniform in character".

More information on the physical properties of sea water is available in references [1-5].

2. THE COMPUTATIONAL PROCEDURE

At present a method does not exist for accurately measuring sea water density *in situ* (i.e. via an instrument that will directly measure ρ when it is immersed in water). However, CTD (Conductivity, Temperature, Depth) and STD (Salinity, Temperature, Depth) instruments [1] enable sea water temperature and salinity vs. depth profiles to be easily and accurately measured *in situ*. This temperature and salinity data is often used to calculate underwater sound speed profiles via any one of a number of empirically determined equations [6]. These equations link the variables s, t, d and c; where d $\{\mathrm{m}\}$ is the depth and c $\{\mathrm{m\ s^{-1}}\}$ is the velocity of sound. In a similar manner, the empirically determined *International Equation of State of Sea Water (IES 80)* [2, 7] can be used to calculate a sea water density profile. Equation IES 80 takes the form

$$\rho(s,t,p) = \rho(s,t,0)/\left[1 - p/K(s,t,p)\right], \tag{2}$$

where $\rho(s,t,0)$ is the density of sea water at one standard atmosphere pressure (which is by definition when $p = 0$), and $K(s,t,p)$ is the secant bulk modulus of sea water.

Equations for $\rho(s,t,0)$ and $K(s,t,p)$ appear in references [2, 7], and take the form of complicated polynomial expressions in s, t and p.

The procedure for calculating $\rho(d)$ that is presented in this report uses equation (2) and the polynomial expressions for $\rho(s,t,0)$ and $K(s,t,p)$ appearing in references [2, 7]. So that a $\rho(d)$ profile can be calculated directly from supplied $s(d)$ and $t(d)$ profiles, the procedure incorporates a means of calculating the required $p(d)$ profile. This is done as follows: p and ρ values are simultaneously determined by stepping down in "small" depth increments Δd from the sea surface, and using the current value of ρ and the formula $\Delta p = \rho g \Delta d$ to calculate the increase in p over the increment. The resulting upgraded value of p is then used in equation (2) to upgrade the value of ρ. Note that while performing these calculations, local values of s and t are determined by interpolating the supplied data points.

A reference that presents a more sophisticated procedure for calculating $\rho(s,t,p)$ is [8]. This reference is recommended reading for those who wish to calculate the seawater density, and more so its gradient, with *high precision.* The procedure presented here differs in the fact that it is designed for those who have existing temperature and salinity profile data, and who wish to determine the corresponding density profile without reference to pressure data. It is the author's opinion that this procedure will yield a density profile that can be considered to be at least a good first approximation to the true density profile, especially at shallow water depths (i.e. less than a few 100 m).

A FORTRAN computer program called *dencalc.f* (see Appendix) has been written which calculates $\rho(d)$ from $s(d)$ and $t(d)$ data via the procedure described above. The algorithmic steps followed in this program are:

1. Read $s(d)$, $t(d)$ data. Note that this data may be specified at varying depth increments.

2. Interpolate $s(d)$, $t(d)$ data using natural cubic splines [9].

3. Begin density calculations at the sea surface ($i = 0$) by setting $p_i = 0$, and calculating $\rho_i = \rho(s_i, t_i, p_i)$ using equation IES 80 and the surface values of temperature and salinity (s_i, t_i).

4. Setting $i = 1, 2, 3, \ldots$ step down from the sea surface in "small" equal depth increments Δd, and iteratively calculate the pressure and density (from equation IES 80) at each step as follows:

$$p_i = p_{i-1} + \rho_{i-1} g \Delta d, \tag{3}$$

$$\rho_i = \rho(s_i, t_i, p_i). \tag{4}$$

In equations (3) and (4), $g = 9.8$ m s^{-1} is gravitational acceleration, and s_i, t_i are the interpolated values of salinity and temperature at the depth $d = i * \Delta d$.

3. RESULTS OF CALCULATIONS

Density calculations have been performed using temperature and salinity vs. depth data from the AKARANA Sea Trials [10]. Figure 1 is taken from reference [10], and shows the data gathering sites for these trials. Tables 1-6 show the data files which were obtained from reference [10] and used as input for the program *dencalc.f*. Tables 7-9 show shortened versions of the output data files produced by *dencalc.f* when AKARANA site G was considered. Plots of the temperature, salinity and density data obtained from *dencalc.f* for all AKARANA sites appear in figures 2-19. Note that when producing these data, the depth increment $\Delta d = 2$ m was used.

Some interesting observations can be made from the plots appearing in figures 2-19. Notice from figures 2, 5, 8, 11, 14 and 17 that as one proceeds from site B (the southernmost site) up to site G (the northernmost site), the surface temperature of the ocean increases. Accompanying the increased surface temperatures are greater changes in temperature over the thermocline zone. These characteristics are reflected in the density curves appearing in figures 4, 7, 10, 13, 16 and 19 where greater variations in density over the thermocline zone are observed at the more northerly sites. Notice also from these figures that the density is seen to increase uniformly with depth at depths greater than approximately 800 m, due to the dominating effect of increasing water pressure. The salinity curves shown in figures 3, 6, 9, 12, 15 and 18 show no significant trends apart from the fact that the salinity of surface waters is slightly greater at the more southerly sites. The observed variations in salinity only play a minor role in determining the form of the density profiles.

4. CONCLUSION

Details have been given of a computational procedure for calculating an ocean mass density stratification from temperature and salinity data. This began with a presentation of some general facts about ocean density, temperature and salinity stratifications. The specific details of the computational procedure were then presented. The procedure utilizes the empirically determined International Equation of State of Sea Water (IES 80), and has been implemented in the FORTRAN computer program *dencalc.f* which appears in the attached Appendix. Temperature and salinity data obtained from the AKARANA sea trials were then used to calculate ocean density stratifications at a number of locations in waters to the West and North-West of Australia. An examination of the results of these calculations showed that the greatest temperature variations occurred in the northern waters, and that this resulted in greater variations in the accompanying density stratifications. At depths below approximately 800 m the effect of pressure upon the density stratifications was seen to dominate, yielding linear density profiles.

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```
c
c                        ________________________
c                       |                        |
c                       |        APPENDIX        |
c                       |________________________|


      program   DENCALC

c This program reads temperature and salinity vs. depth data from the
c file 'dencalc.inp' and calculates the corresponding density profile
c at a specified number of equispaced points.  The program writes
c either temperature, salinity or density vs. depth data at the
c specified points to the file 'dencalc.out', ready for plotting.
c The program is based upon the theory presented in the MRL Technical
c Note "Ocean Mass Density Calculations from Temperature and Salinity
c Data" by G.D. Furnell (1994).

c Graham Furnell, May 1994.


      implicit   none

      integer   maxndata, maxnden

      parameter   (maxndata = 1000, maxnden = 2000)

      integer   i, ndata, nden, flag

      real    depth_data(maxndata), temp_data(maxndata),
     &        salin_data(maxndata), temp_coeff(maxndata),
     &        salin_coeff(maxndata), depth(maxnden),
     &        temp(maxnden), salin(maxnden), density(maxnden),
     &        yp1, ypn, span, step, dumx, dumy, g, p, delp, k,
     &        denzero, bulkmod

      character*60   string(5)


c Reading in temperature and salinity data from the file 'dencalc.inp'
c and calculating the corresponding spline coefficients.

      write(6,*)
      write(6,*) 'Processing temperature and salinity input data.'
      write(6,*) '-----------------------------------------------'

      open(unit=7, file='dencalc.inp')
 5    format(A60)

      do i = 1,5
        read(7,5) string(i)
      end do
      read(7,*)
      read(7,*)
      do i = 1,maxndata
        read(7,*,end=10) depth_data(i), temp_data(i), salin_data(i)
      end do
 10   ndata = i - 1

      yp1 = 1.0E30
      ypn = 1.0E30

      call spline(depth_data, temp_data, ndata, yp1, ypn, temp_coeff)
      call spline(depth_data, salin_data, ndata, yp1, ypn, salin_coeff)
```

```
c  Calculating the spline interpolated values of temperature and salinity.

       write(6,*)
       write(6,*) 'Input number of points for density profile calculation: '
       write(6,*) '-------------------------------------------------------- '
       read(5,*) nden

       span = depth_data(ndata) - depth_data(1)
       step = span/FLOAT(nden-1)

       do i = 1,nden
         depth(i) = depth_data(1) + FLOAT(i-1)*step
         dumx = depth(i)
         call splint(depth_data, temp_data, temp_coeff, ndata, dumx, dumy)
         temp(i) = dumy
         call splint(depth_data, salin_data, salin_coeff, ndata, dumx, dumy)
         salin(i) = dumy
       end do

c  Calculating density profile.
c  Note the following units:
c              pressure        'p', 'delp'      {bar} (= 10**5 Pa)
c              density         'density'        {kg/m**3}
c              length          'depth'          {m}
c              salinity        'salin'          {parts/1000}
c              temperature     'temp'           {degrees C}
c              gravity         'g'              {m/s**2}

       g = 9.80665
       density(1) = denzero(salin(1), temp(1))
       p = 0.0     !   i.e. Pressure defined to be zero at sea surface.

       do i = 2,nden
         delp = density(i-1)*g*step*1.0E-5    ! Note: Factor 1.0E-5 included
         p = p + delp                         !       to express delp in bar.
         k = bulkmod(salin(i), temp(i), p)
         density(i) = denzero(salin(i), temp(i))/(1.0 - p/k)
       end do

c  Writing output to file 'dencalc.out'.

       open(unit=8, file='dencalc.out')

       write(8,*) 'DENCALC OUTPUT DATA'
       write(8,*) '==================='
       write(8,*)
       do i = 1,5
         write(8,5) string(i)
       end do
       write(8,*)
       write(8,20) nden
   20  format('Number of points in output = ', I4)
       write(8,*)

   30  write(6,*)
       write(6,*) 'Input 1/2/3 for temperature/salinity/density output: '
       write(6,*) '---------------------------------------------------- '
       read(5,*) flag

       if (flag.EQ.1) then
         write(8,*) '     DEPTH      TEMPERATURE'
         write(8,*) '-------------------------------'
         do i = 1,nden
           write(8,*) depth(i), temp(i)
         end do
```

```
      else if (flag.EQ.2) then
        write(8,*) '     DEPTH     SALINITY'
        write(8,*) '---------------------------'
        do i = 1,nden
          write(8,*) depth(i), salin(i)
        end do
      else if (flag.EQ.3) then
        write(8,*) '     DEPTH     DENSITY'
        write(8,*) '--------------------------'
        do i = 1,nden
          write(8,*) depth(i), density(i)
        end do
      else
        write(6,*)
        write(6,*) 'Number input out of range.'
        write(6,*) '-------------------------'
        write(6,*)
        go to 30
      end if

c  End of program.

      write(6,*)
      write(6,*) 'End of program.'
      write(6,*) '---------------'
      write(6,*)


      end



      subroutine   spline(x,y,n,yp1,ypn,y2)

c  This subroutine is from P.88 of the book "Numerical Recipes - The Art
c  of Scientific Computing" by W.H. Press, et. al. (1988).
c  Given arrays "x" and "y" of length "n" containing a tabulated function,
c  i.e. y_i = f(x_i), with x_1 < x_2 < ... < x_n, and given values "yp1"
c  and "ypn" for the first derivative of the interpolating function at
c  points 1 and n, respectively, this routine returns an array "y2" of
c  length n which contains the second derivatives of the interpolating
c  function at the tabulated points x_i.  If yp1 and/or ypn are equal
c  to 1 x 10**30 or larger, the routine is signalled to set the
c  corresponding boundary condition for a natural spline, with zero
c  second derivative on that boundary.

      parameter    (nmax=100)          ! nmax = max. no. of x,y values.
      dimension    x(n), y(n), y2(n), u(nmax)

      if (yp1.GT.0.99E30) then         ! Set lower bound end conditions
        y2(1) = 0.0                    ! "natural" cond.
        u(1) = 0.0
      else
        y2(1) = - 0.5                  ! "first derivative" cond.
        u(1) = (3.0/(x(2)-x(1)))*((y(2)-y(1))/(x(2)-x(1))-yp1)
      end if

      do i=2,n-1                       ! Form tridiag. system for coeffs.
        sig = (x(i)-x(i-1))/(x(i+1)-x(i-1))
        p = sig*y2(i-1) + 2.0
        y2(i) = (sig-1.0)/p
        u(i) = (6.0*((y(i+1)-y(i))/(x(i+1)-x(i))-(y(i)-y(i-1))
     &         /(x(i)-x(i-1)))/(x(i+1)-x(i-1))-sig*u(i-1))/p
      end do
```

```
      if (ypn.GT.0.99E30) then         ! Set upper bound end conditions.
        qn = 0.0                       ! "natural" cond.
        un = 0.0
      else
        qn = 0.5                       ! "first derivative" cond.
        un = (3.0/(x(n)-x(n-1)))*(ypn-(y(n)-y(n-1))/(x(n)-x(n-1)))
      end if
      y2(n) = (un-qn*u(n-1))/(qn*y2(n-1)+1.0)

      do k=n-1,1,-1                    ! Solve for coeffs by back subn.
        y2(k) = y2(k)*y2(k+1)+u(k)
      end do

      return
      end



      subroutine   splint(xa,ya,y2a,n,x,y)

c This subroutine is from P.89 of the book "Numerical Recipes - The Art
c of Scientific Computing" by W.H. Press, et. al. (1988).
c Given the arrays "xa" and "ya" of length "n", which tabulate a function
c (with the xa_i's in order), and given the array "y2a", which is the
c output from "spline" above, and given a value of "x", this routine
c returns a cubic-spline interpolated value "y".

      dimension   xa(n), ya(n), y2a(n)

      klo = 1
      khi = n
1     if (khi-klo.GT.1) then           ! Find right coeffs. which bracket
        k = (khi+klo)/2                ! x via bisection.
        if (xa(k).GT.x) then
          khi = k
        else
          klo = k
        end if
        go to 1
      end if

      h = xa(khi) - xa(klo)
      if (h.EQ.0.0)   pause 'Bad XA input in subroutine splint'
      a = (xa(khi)-x)/h                ! Cubic spline now evaluated.
      b = (x-xa(klo))/h
      y = a*ya(klo)+b*ya(khi)+
     &    ((a**3-a)*y2a(klo)+(b**3-b)*y2a(khi))*(h**2)/6.0

      return
      end



      real function   denzero(s,t)

c Given the salinity "s" and temperature "t", this function returns
c the density of sea water at one standard atmosphere pressure from the
c formula supplied in Appendix 3 of the book "Introductory Dynamical
c Oceanography" 2nd ed. by S. Pond and G.L. Pickard (1983).

      implicit   none

      real   s, t
```

```
      denzero =  + 999.842594              + 6.793952E-2*t
     &           - 9.095290E-3*t**2        + 1.001685E-4*t**3
     &           - 1.120083E-6*t**4        + 6.536332E-9*t**5
     &           + 8.24493E-1       *s     - 4.0899E-3  *t   *s
     &           + 7.6438E-5   *t**2*s     - 8.2467E-7  *t**3*s
     &           + 5.3875E-9   *t**4*s     - 5.72466E-3      *s**1.5
     &           + 1.0227E-4   *t   *s**1.5 - 1.6546E-6  *t**2*s**1.5
     &           + 4.8314E-4        *s**2

      return
      end


      real function   bulkmod(s,t,p)

c  Given the salinity "s", temperature "t" and pressure "p", this
c  function calculates the secant bulk modulus of seawater from the
c  formula supplied in Appendix 3 of the book "Introductory Dynamical
c  Oceanography" 2nd ed. by S. Pond and G.L. Pickard (1983).

      implicit   none

      real    s, t, p


      bulkmod =
     & + 19652.21
     & + 148.4206   *t                  - 2.327105   *t**2
     & + 1.360477E-2*t**3               - 5.155288E-5*t**4
     & + 3.239908          *p           + 1.43713E-3 *t    *p
     & + 1.16092E-4 *t**2*p             - 5.77905E-7 *t**3*p
     & + 8.50935E-5        *p**2        - 6.12293E-6 *t    *p**2
     & + 5.2787E-8  *t**2*p**2
     & + 54.6746                *s      - 0.603459   *t          *s
     & + 1.09987E-2 *t**2       *s      - 6.1670E-5  *t**3       *s
     & + 7.944E-2               *s**1.5 + 1.6483E-2  *t          *s**1.5
     & - 5.3009E-4  *t**2       *s**1.5 + 2.2838E-3        *p    *s
     & - 1.0981E-5  *t    *p    *s      - 1.6078E-6  *t**2*p     *s
     & + 1.91075E-4       *p    *s**1.5 - 9.9348E-7        *p**2*s
     & + 2.0816E-8  *t    *p**2*s       + 9.1697E-10 *t**2*p**2*s

      return
      end
```

Table 1: Temperature and salinity input data for AKARANA site B

HMNZS TUI
T218 AKARANA
31deg 36min S 110deg 38min E
19 NOV 1980 0200Z
CTD STATION NO 9, SITE B

DEPTH	TEMPERATURE	SALINITY
0.0	18.10	35.84
10.0	18.10	35.84
20.0	18.09	35.83
30.0	18.05	35.83
40.0	18.02	35.82
50.0	18.00	35.82
60.0	17.78	35.87
70.0	17.44	35.84
75.0	17.23	35.85
80.0	17.21	35.87
90.0	17.10	35.87
100.0	16.56	35.79
110.0	16.38	35.80
120.0	15.94	35.79
130.0	15.42	35.70
140.0	15.06	35.67
150.0	14.87	35.66
160.0	14.90	35.68
170.0	14.80	35.66
180.0	14.70	35.76
190.0	14.55	35.61
200.0	14.53	35.62
250.0	13.78	35.48
300.0	12.97	35.32
350.0	11.69	35.08
400.0	10.85	34.94
450.0	10.27	34.85
500.0	9.90	34.81
550.0	9.56	34.77
600.0	9.15	34.73
650.0	8.81	34.69
700.0	8.47	34.61
750.0	7.92	34.60
800.0	7.18	34.54
850.0	6.42	34.50
900.0	5.66	34.47
950.0	5.01	34.45
1000.0	4.57	34.44
1050.0	4.22	34.46
1100.0	4.01	34.49
1150.0	3.55	34.48
1200.0	3.43	34.51
1250.0	3.31	34.52
1300.0	3.20	34.54
1350.0	3.27	34.60
1400.0	3.20	34.62
1450.0	3.15	34.63
1500.0	3.02	34.65
1550.0	2.84	34.65
1600.0	2.81	34.67
1650.0	2.72	34.68
1700.0	2.66	34.69
1750.0	2.63	34.71
1800.0	2.56	34.72

Table 2: Temperature and salinity input data for AKARANA site C

HMNZS TUI
T218 AKARANA
28deg 08min S 109deg 17min E
22 OCT 1980 0800Z
CTD STATION NO 10, SITE C

DEPTH	TEMPERATURE	SALINITY
0.0	19.50	35.67
10.0	19.50	35.67
20.0	19.43	35.64
30.0	19.39	35.68
40.0	18.97	35.80
50.0	18.72	35.83
60.0	18.53	35.86
70.0	18.47	35.87
75.0	18.45	35.87
80.0	18.38	35.88
90.0	18.21	35.88
100.0	17.97	35.89
110.0	17.69	35.88
120.0	17.18	35.92
130.0	17.03	35.85
140.0	16.49	35.78
150.0	16.41	35.83
160.0	16.27	35.83
170.0	16.01	35.80
180.0	15.87	35.78
190.0	15.78	35.78
200.0	15.60	35.78
250.0	14.54	35.58
300.0	13.43	35.40
350.0	11.99	35.13
400.0	10.65	34.90
450.0	10.07	34.83
500.0	9.50	34.78
550.0	9.12	34.72
600.0	8.76	34.88
650.0	8.34	34.64
700.0	7.73	34.59
750.0	6.93	34.53
800.0	6.01	34.46
850.0	5.52	34.50
900.0	4.91	34.51
950.0	4.68	34.54
1000.0	4.54	34.54
1050.0	4.04	34.53
1100.0	4.04	34.57
1150.0	3.79	34.57
1200.0	3.70	34.58
1250.0	3.63	34.59
1300.0	3.59	34.61
1350.0	3.35	34.62
1400.0	3.28	34.64
1450.0	3.24	34.66
1500.0	3.08	34.66
1550.0	3.07	34.58
1600.0	2.95	34.59
1650.0	2.84	34.70
1700.0	2.77	34.72
1750.0	2.71	34.72
1800.0	2.62	34.73
1900.0	2.48	34.75
2000.0	2.37	34.76
2100.0	2.26	34.76
2200.0	2.18	34.76
2300.0	2.09	34.77
2400.0	2.02	34.77
2500.0	1.94	34.77
2600.0	1.87	34.77
2700.0	1.80	34.77

Table 3: Temperature and salinity input data for AKARANA site D

HMNZS TUI
T218 AKARANA
18deg 15min S 116deg 08min E
31 OCT 1980 1200Z
CTD STATION NO 11, SITE D

DEPTH	TEMPERATURE	SALINITY
0.0	26.51	34.94
10.0	26.21	34.89
20.0	25.90	34.91
30.0	25.86	34.91
40.0	25.81	34.91
50.0	25.77	34.90
60.0	25.53	34.87
70.0	24.27	34.83
75.0	23.78	34.84
80.0	23.42	34.83
90.0	22.70	34.84
100.0	22.43	34.85
110.0	21.85	34.86
120.0	21.00	34.90
130.0	20.26	34.87
140.0	19.49	34.97
150.0	18.70	35.03
160.0	18.15	35.18
170.0	18.12	35.19
180.0	17.40	35.18
190.0	17.10	35.22
200.0	16.77	35.23
250.0	13.08	34.85
300.0	11.73	34.88
350.0	10.83	34.88
400.0	9.65	34.79
450.0	8.91	34.75
500.0	8.23	34.71
550.0	7.49	34.61
600.0	6.96	34.67
650.0	6.53	34.67
700.0	6.16	34.66
750.0	5.89	34.66
800.0	5.68	34.67
850.0	5.51	34.66
900.0	5.34	34.66
950.0	5.16	34.66
1000.0	4.95	34.66
1050.0	4.58	34.67
1100.0	4.57	34.67
1150.0	4.42	34.67
1200.0	4.29	34.67

Table 4: Temperature and salinity input data for AKARANA site E

```
HMNZS TUI
T218 AKARANA
14deg 36min S  116deg 45min E
2 NOV 1980  1200Z
CTD STATION NO 12, SITE E
```

DEPTH	TEMPERATURE	SALINITY
0.0	28.62	34.47
10.0	28.62	34.47
20.0	28.63	34.51
30.0	28.51	34.37
40.0	28.49	34.41
50.0	27.81	34.36
60.0	27.09	34.52
70.0	27.17	34.38
75.0	26.95	34.39
80.0	26.79	34.39
90.0	26.64	34.49
100.0	26.16	34.55
110.0	24.50	34.36
120.0	23.68	34.41
130.0	22.44	34.46
140.0	21.79	34.49
150.0	24.67	34.47
160.0	19.80	34.41
170.0	18.61	34.41
180.0	18.52	34.67
190.0	18.65	35.01
200.0	17.74	34.97
250.0	13.69	34.72
300.0	12.15	34.75
350.0	10.81	34.83
400.0	9.85	34.81
450.0	9.04	34.76
500.0	8.29	34.71
550.0	7.68	34.68
600.0	7.21	34.67
650.0	6.86	34.66
700.0	6.48	34.67
750.0	6.13	34.68
800.0	5.76	34.66
850.0	5.52	34.66
900.0	5.20	34.65
950.0	5.02	34.65
1000.0	4.80	34.65
1050.0	4.64	34.65
1100.0	4.47	34.66
1150.0	4.30	34.66
1200.0	4.18	34.67
1250.0	4.03	34.67
1300.0	3.91	34.68
1350.0	3.78	34.69
1400.0	3.63	34.70
1450.0	3.49	34.71
1500.0	3.50	34.71
1550.0	3.26	34.72
1600.0	3.13	34.73
1650.0	3.01	34.75
1700.0	2.92	34.74
1750.0	2.81	34.75
1800.0	2.71	34.76
1900.0	2.53	34.77
2000.0	2.39	34.77
2100.0	2.26	34.77
2200.0	2.14	34.77
2300.0	2.05	34.77
2400.0	1.97	34.77

Table 5: Temperature and salinity input data for AKARANA site F

```
HMNZS TUI
T218 AKARANA
13deg 18min S  114deg 38min E
14 NOV 1980  0100Z
CTD STATION NO 15, SITE F
```

DEPTH	TEMPERATURE	SALINITY
0.0	28.56	34.53
10.0	28.56	34.54
20.0	28.52	34.53
30.0	28.52	34.53
40.0	28.52	34.54
50.0	28.51	34.53
60.0	27.40	34.40
70.0	26.91	34.34
75.0	26.76	34.41
80.0	26.29	34.33
90.0	25.84	34.32
100.0	25.40	34.42
110.0	24.10	34.35
120.0	22.61	34.40
130.0	21.82	34.51
140.0	20.95	34.65
150.0	19.90	34.77
160.0	18.72	34.62
170.0	17.55	34.54
180.0	16.83	34.50
190.0	16.52	34.68
200.0	15.76	34.71
250.0	12.85	34.70
300.0	11.30	34.73
350.0	10.46	34.81
400.0	9.71	34.80
450.0	8.72	34.70
500.0	7.99	34.69
550.0	7.56	34.69
600.0	7.11	34.68
650.0	6.81	34.55
700.0	6.34	34.66
750.0	6.04	34.65
800.0	5.75	34.65
850.0	5.55	34.65
900.0	5.32	34.65
950.0	5.15	34.65
1000.0	4.92	34.65
1050.0	4.73	34.66
1100.0	4.58	34.65
1150.0	4.40	34.66
1200.0	4.28	34.67
1250.0	4.12	34.67
1300.0	3.97	34.68
1350.0	3.82	34.69
1400.0	3.63	34.70
1450.0	3.52	34.71
1500.0	3.36	34.72
1550.0	3.21	34.73
1600.0	3.09	34.74
1650.0	2.98	34.75
1700.0	2.89	34.76
1750.0	2.78	34.76
1800.0	2.68	34.77
1900.0	2.49	34.77

Table 6: Temperature and salinity input data for AKARANA site G

HMNZS TUI
T218 AKARANA
12deg 28min S 122deg 18min E
17 NOV 1980 1230Z
CTD STATION NO 17, SITE G

DEPTH	TEMPERATURE	SALINITY
0.0	30.10	34.70
10.0	29.78	34.66
20.0	29.40	34.62
30.0	29.19	34.61
40.0	28.28	34.47
50.0	27.44	34.40
60.0	26.96	34.48
70.0	26.62	34.56
75.0	25.91	34.58
80.0	25.82	34.61
90.0	25.15	34.63
100.0	24.26	34.55
110.0	23.48	34.64
120.0	21.35	34.56
130.0	20.31	34.55
140.0	19.42	34.51
150.0	18.76	34.48
160.0	18.23	34.53
170.0	17.50	34.68
180.0	17.06	34.59
190.0	16.53	34.59
200.0	15.96	34.56
250.0	12.99	34.63
300.0	11.17	34.60
350.0	9.78	34.61
400.0	9.03	34.61
450.0	8.63	34.64
500.0	8.09	34.62
550.0	7.64	34.62
600.0	7.43	34.63
650.0	6.78	34.64
700.0	6.43	34.64
750.0	6.23	34.63
800.0	5.79	34.64
850.0	5.40	34.64
900.0	5.04	34.64

Table 7: Temperature output data for AKARANA site G

```
DENCALC OUTPUT DATA
===================

HMNZS TUI
T218 AKARANA
12deg 28min S  122deg 18min E
17 NOV 1980  1230Z
CTD STATION NO 17, SITE G

Number of points in output =  451
```

DEPTH	TEMPERATURE
0.	30.1000
2.00000	30.0440
4.00000	29.9861
6.00000	29.9241
8.00000	29.8561
10.00000	29.7800
12.0000	29.6954
14.0000	29.6080
16.0000	29.5248
18.0000	29.4531
20.0000	29.4000
22.0000	29.3689
24.0000	29.3479
26.0000	29.3215
28.0000	29.2741
30.0000	29.1900
.	.
.	.
.	.
.	.
870.000	5.25613
872.000	5.24173
874.000	5.22733
876.000	5.21293
878.000	5.19852
880.000	5.18412
882.000	5.16971
884.000	5.15530
886.000	5.14089
888.000	5.12648
890.000	5.11207
892.000	5.09765
894.000	5.08324
896.000	5.06883
898.000	5.05441
900.000	5.04000

Table 8: Salinity output data for AKARANA site G

DENCALC OUTPUT DATA
===================

HMNZS TUI
T218 AKARANA
12deg 28min S 122deg 18min E
17 NOV 1980 1230Z
CTD STATION NO 17, SITE G

Number of points in output = 451

DEPTH	SALINITY
0.	34.7000
2.00000	34.6929
4.00000	34.6856
6.00000	34.6779
8.00000	34.6694
10.00000	34.6600
12.0000	34.6497
14.0000	34.6394
16.0000	34.6302
18.0000	34.6234
20.0000	34.6200
22.0000	34.6206
24.0000	34.6228
26.0000	34.6237
28.0000	34.6205
30.0000	34.6100
.	.
.	.
.	.
.	.
870.000	34.6396
872.000	34.6396
874.000	34.6396
876.000	34.6396
878.000	34.6396
880.000	34.6396
882.000	34.6396
884.000	34.6397
886.000	34.6397
888.000	34.6397
890.000	34.6398
892.000	34.6398
894.000	34.6399
896.000	34.6399
898.000	34.6400
900.000	34.6400

Table 9: Density output data for AKARANA site G

```
DENCALC OUTPUT DATA
===================

HMNZS TUI
T218 AKARANA
12deg 28min S  122deg 18min E
17 NOV 1980  1230Z
CTD STATION NO 17, SITE G

Number of points in output =  451

      DEPTH      DENSITY
---------------------------
     0.          1021.47
     2.00000     1021.49
     4.00000     1021.51
     6.00000     1021.54
     8.00000     1021.56
    10.00000     1021.59
     12.0000     1021.62
     14.0000     1021.65
     16.0000     1021.68
     18.0000     1021.71
     20.0000     1021.73
     22.0000     1021.75
     24.0000     1021.77
     26.0000     1021.79
     28.0000     1021.81
     30.0000     1021.84

        .           .
        .           .
        .           .
        .           .

     870.000     1031.38
     872.000     1031.39
     874.000     1031.40
     876.000     1031.42
     878.000     1031.43
     880.000     1031.44
     882.000     1031.45
     884.000     1031.46
     886.000     1031.47
     888.000     1031.48
     890.000     1031.49
     892.000     1031.51
     894.000     1031.52
     896.000     1031.53
     898.000     1031.54
     900.000     1031.55
```

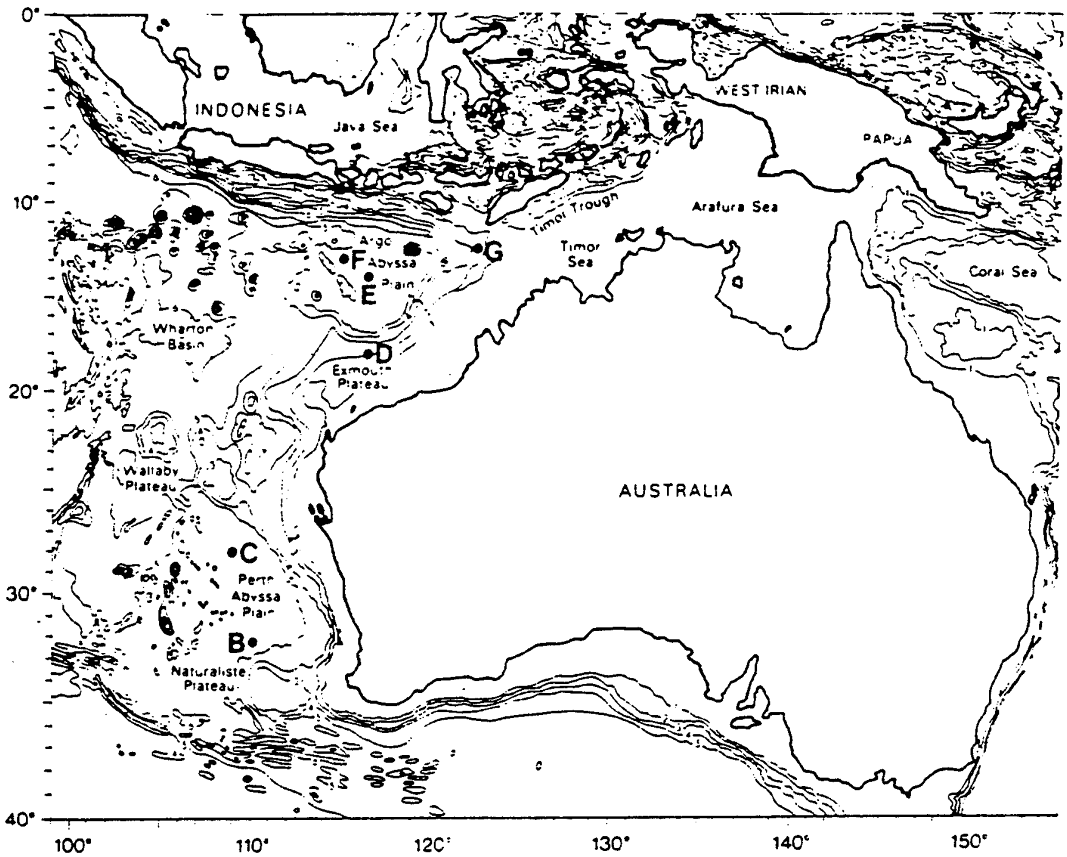

Figure 1: AKARANA sea test sites

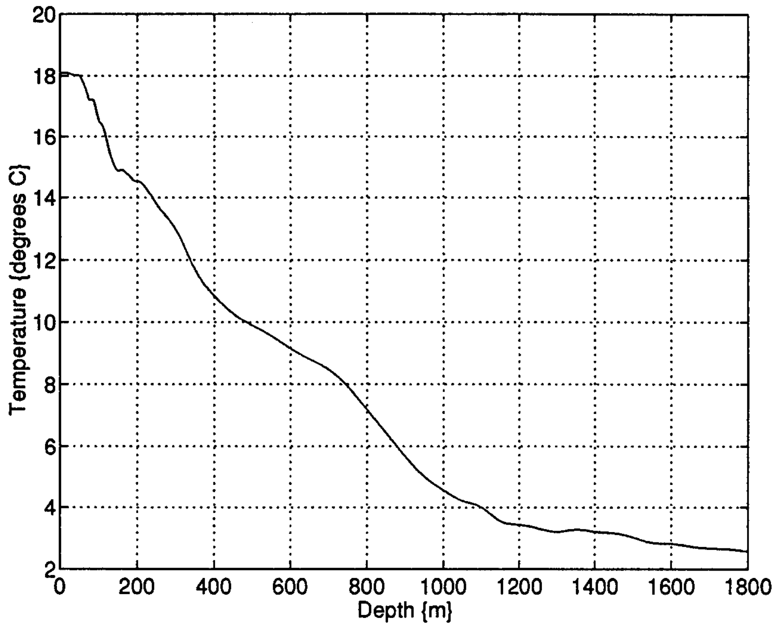

Figure 2: Temperature profile for AKARANA site B

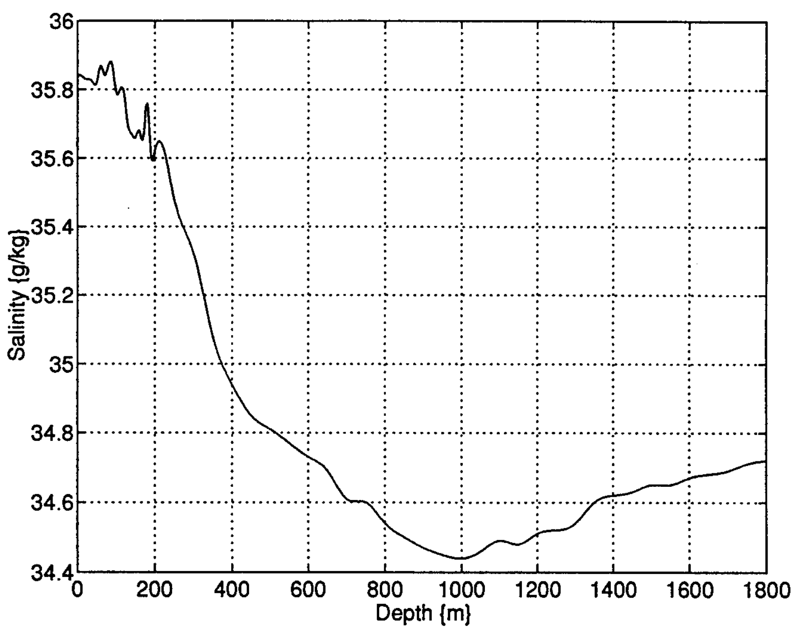

Figure 3: Salinity profile for AKARANA site B

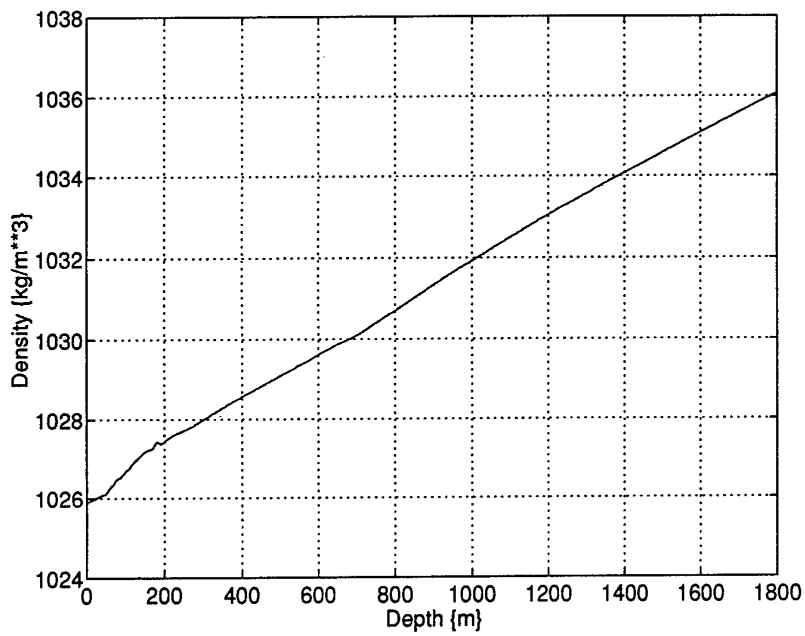

Figure 4: Density profile for AKARANA site B

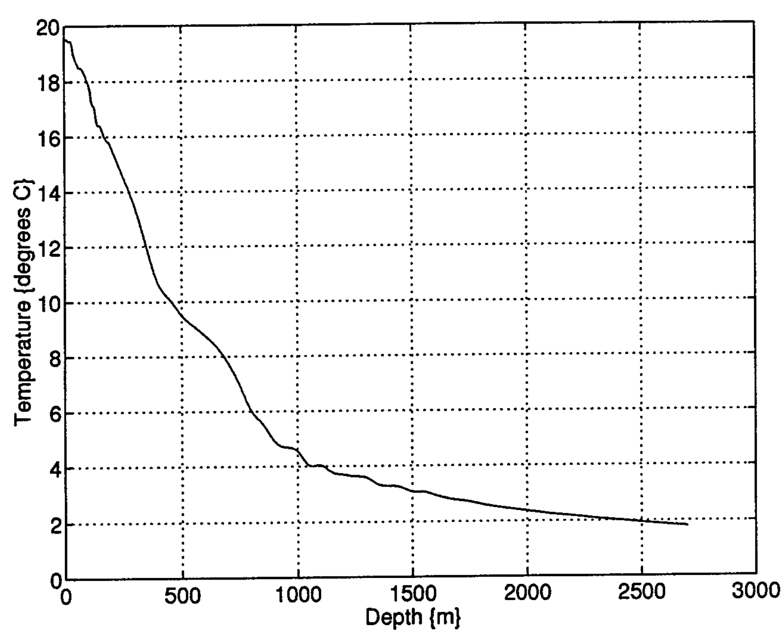

Figure 5: Temperature profile for AKARANA site C

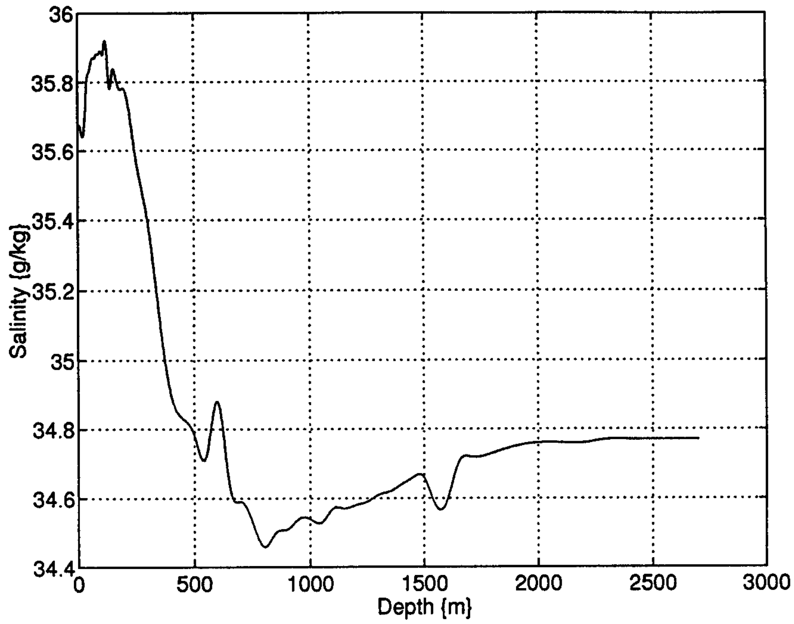

Figure 6: Salinity profile for AKARANA site C

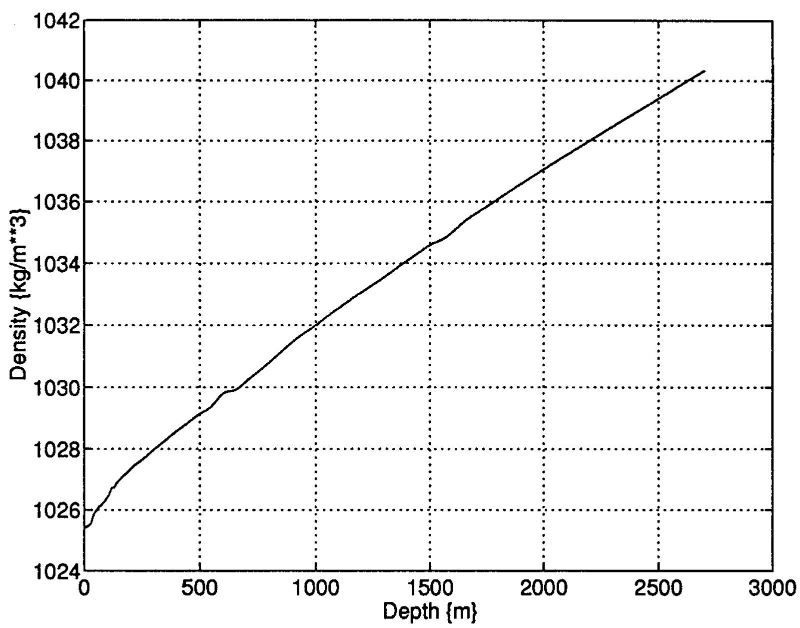

Figure 7: Density profile for AKARANA site C

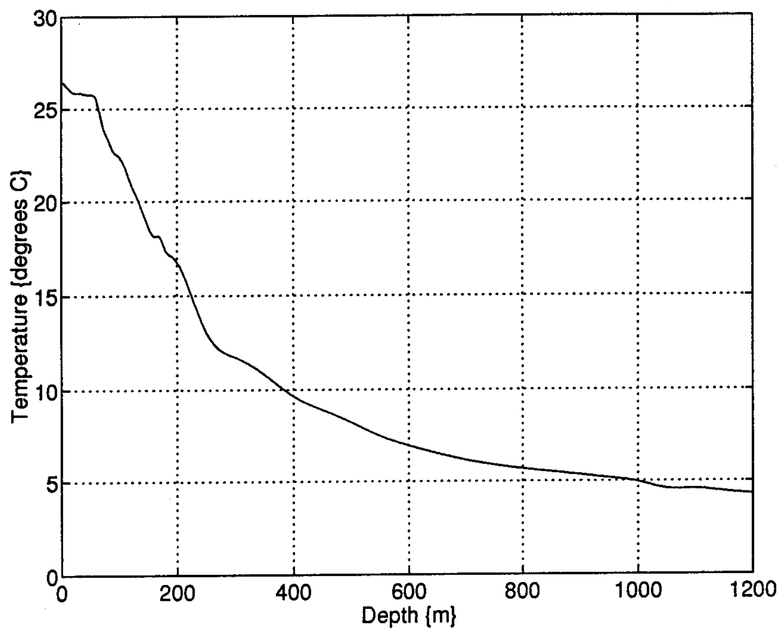

Figure 8: Temperature profile for AKARANA site D

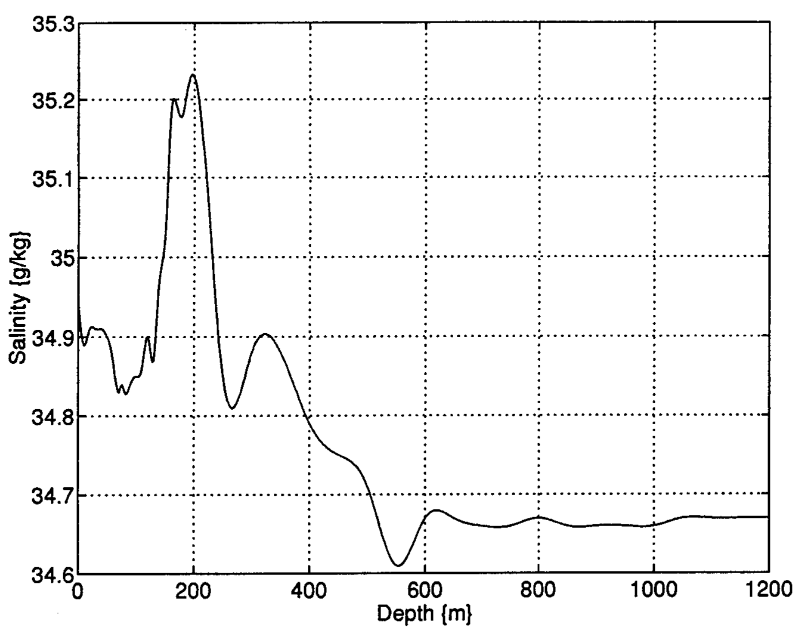

Figure 9: Salinity profile for AKARANA site D

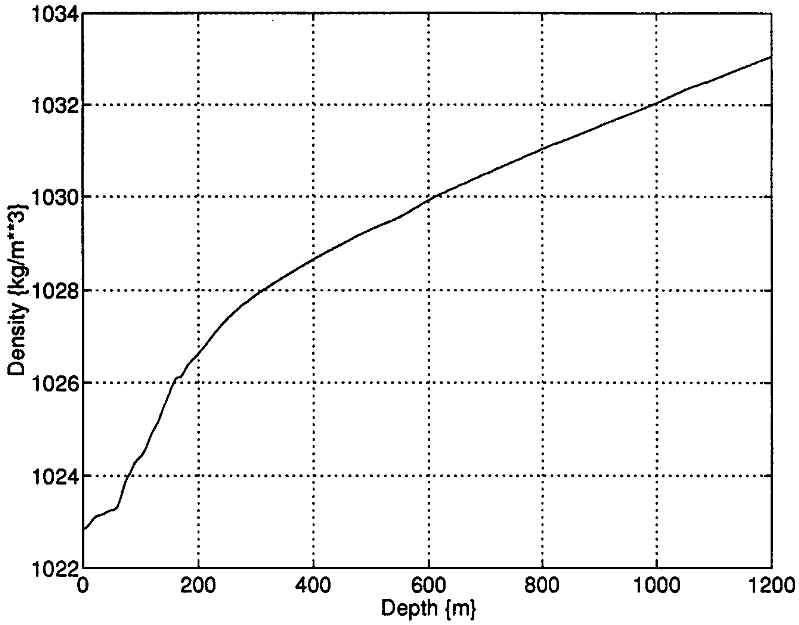

Figure 10: Density profile for AKARANA site D

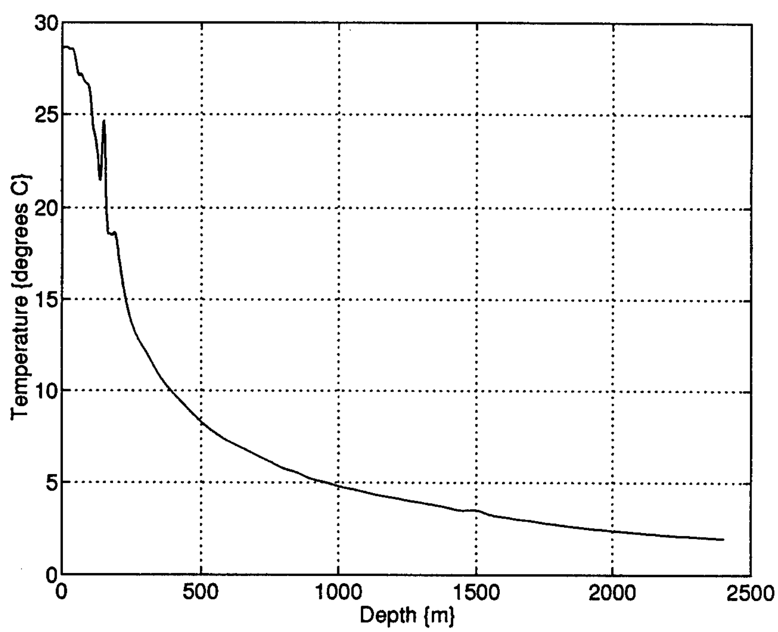

Figure 11: Temperature profile for AKARANA site E

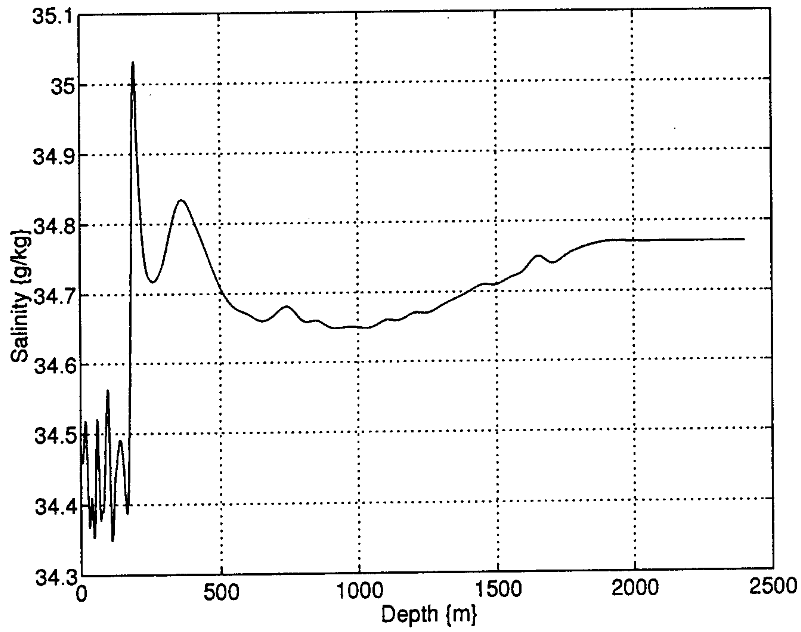

Figure 12: Salinity profile for AKARANA site E

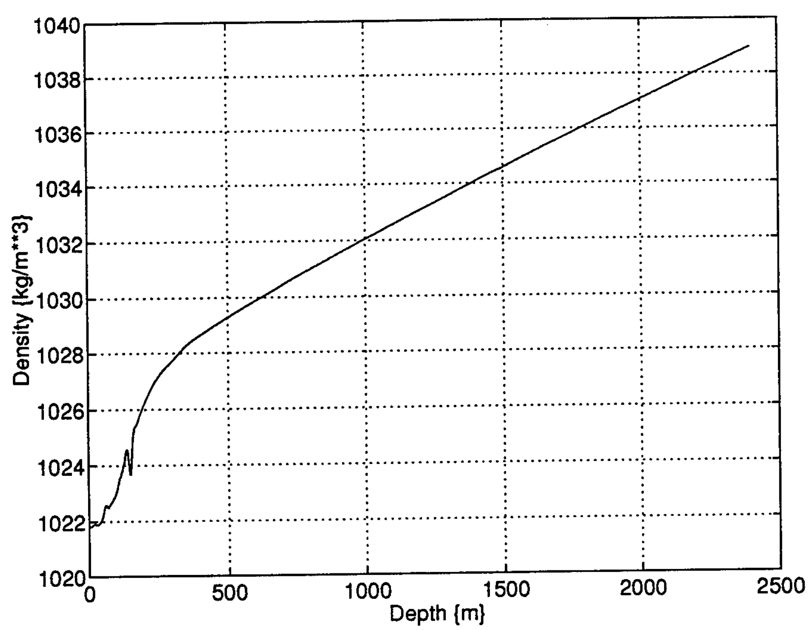

Figure 13: Density profile for AKARANA site E

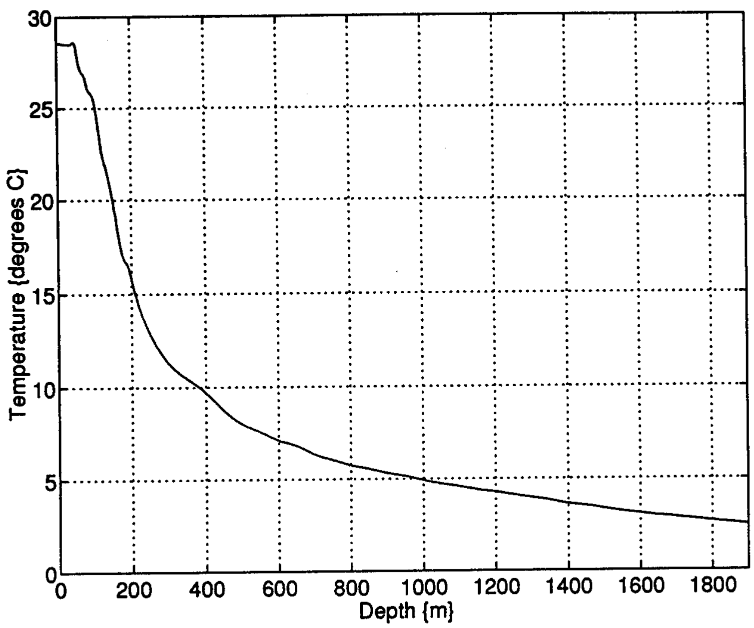

Figure 14: Temperature profile for AKARANA site F

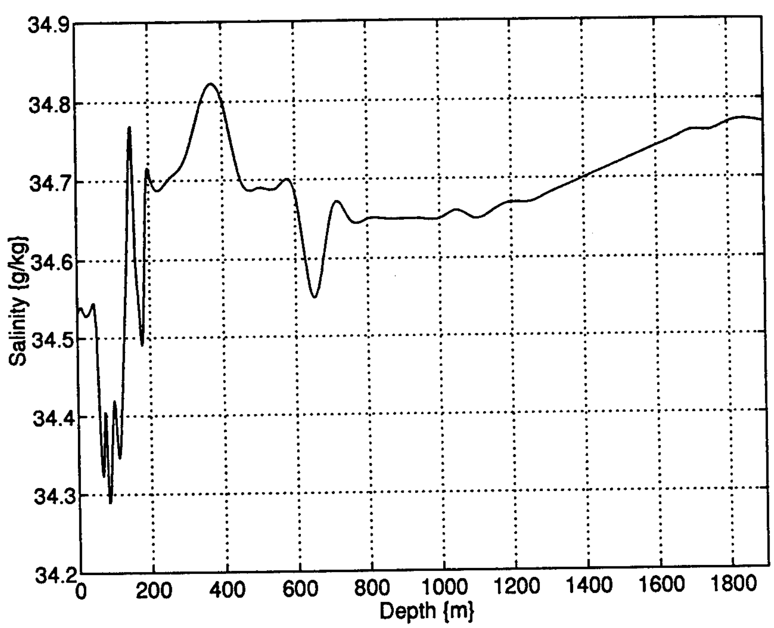

Figure 15: Salinity profile for AKARANA site F

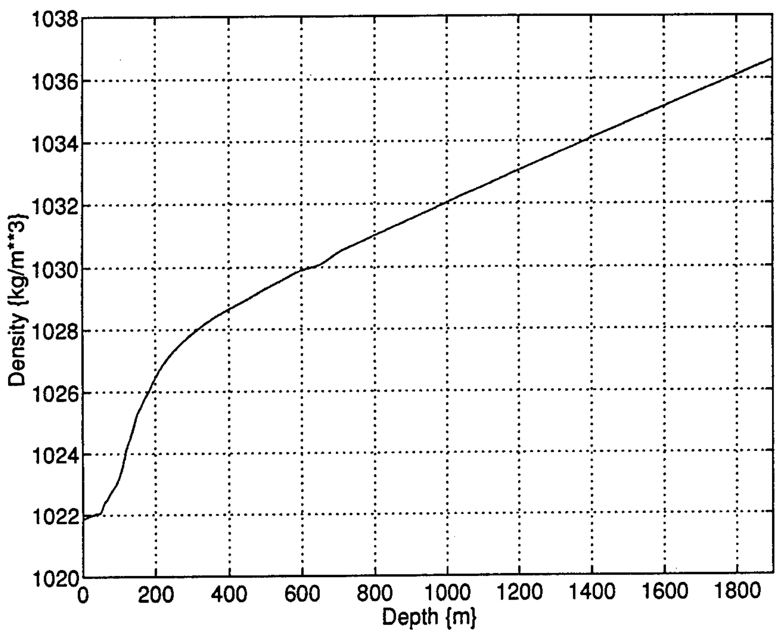

Figure 16: Density profile for AKARANA site F

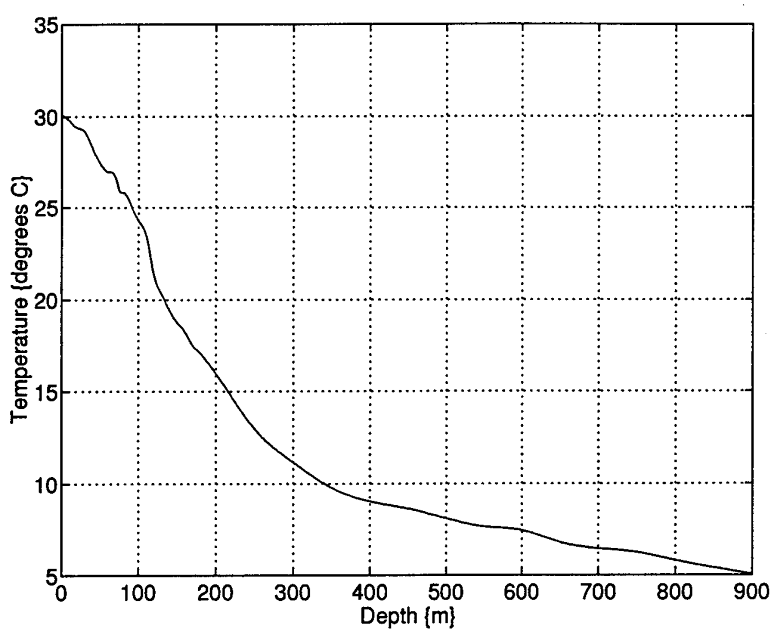

Figure 17: Temperature profile for AKARANA site G

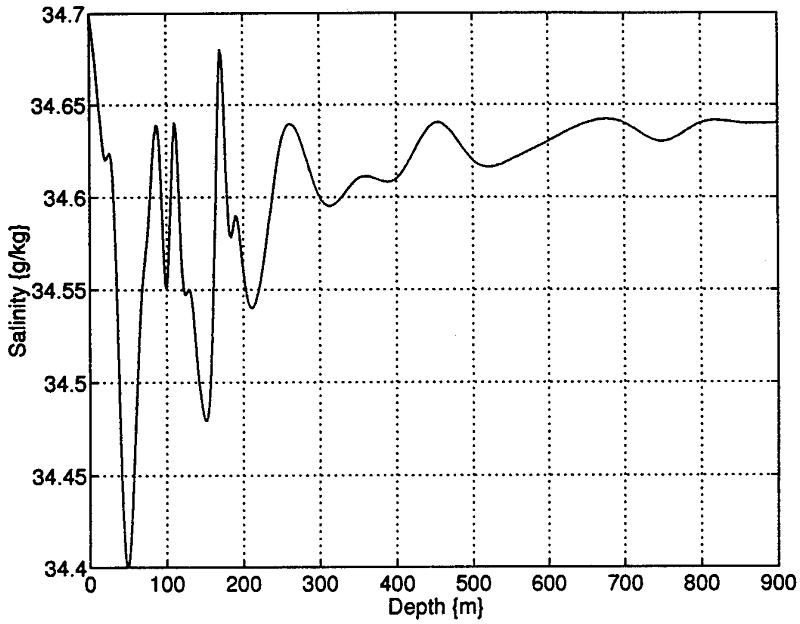

Figure 18: Salinity profile for AKARANA site G

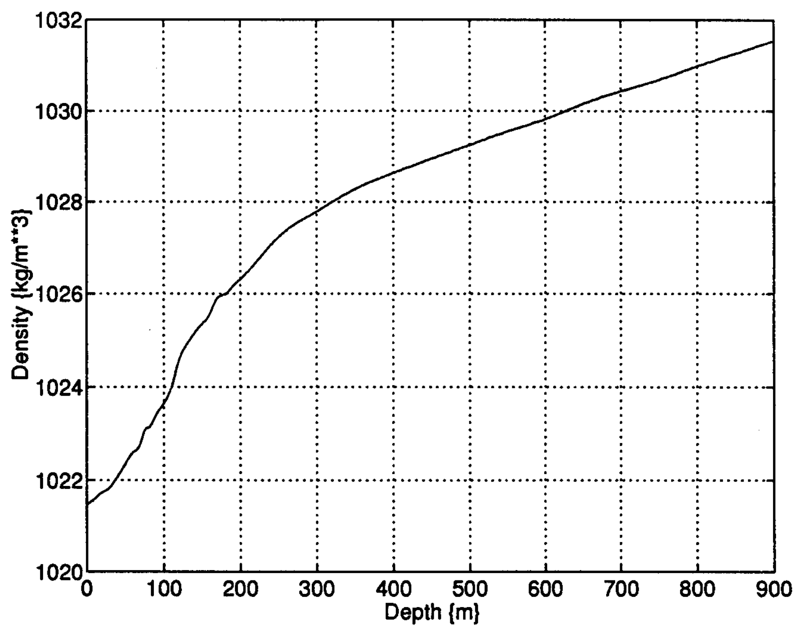

Figure 19: Density profile for AKARANA site G

Ocean Mass Density Calculations from Temperature and Salinity Data

G.D. Furnell

DSTO-TR-0023

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Ocean mass density calculations from temperature and salinity data

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ABSTRACT

A knowledge of the mass density stratification of ocean waters is a fundamental requirement when performing calculations in the field of dynamical oceanography. Experimentally, ocean temperature and salinity stratifications can be conveniently measured. In this report, details are given of a computational procedure which uses the International Equation of State of Sea Water (IES 80) to calculate an ocean mass density stratification from temperature and salinity data. The results of calculations are presented which yield mass density stratifications at a number of locations in waters to the West and North-West of Australia.